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Digital Computer Control of Advanced Waste Treatment Systems

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16. ABSTRACT
The objectives of the study were to develop and demonstrate automatic control strategies using a digital computer on advanced wastewater treatment systems. Two basic pilot treatment systems were automated, physical-chemical treatment and the three-stage activated sludge system. The digital automation involved control of lime feeding, pH control with CO_2, $FeCl_3$, sludge wasting, and breakpoint chlorination in the physical-chemical system. In the biological system, the automation involved $FeCl_3$ dosage and D.O. control in aeration, pH control in nitrification and CH_3OH and alum dosage controls in denitrification. The digital control approaches satisfactorily operated the pilot plants.

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FOREWORD

The Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems for the prevention, treatment, and management of wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, for the preservation and treatment of public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research; a most vital communications link between the researcher and the user community.

This report presents the development of digital computer control of advanced wastewater treatment systems. The report includes an evaluation of the digital control technology with respect to analog and manual control. It provides information for selecting process control systems and thereby reduces the adverse effects of pollution on man and his environment.

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ABSTRACT

Stringent water quality requirements, particularly of effluent quality, demand the application of new control technology to wastewater treatment systems. The principal goal of this study was the development of a digital computer control system for operation of wastewater treatment processes. A brief comparison of the operation using digital control with the operation using existing manual and analog control was also performed.

An IBM digital computer (System 7), with flexible hardware and software, was placed at the EPA-DC Pilot Plant. The computer through a fixed disc and associated software contained the capacity for storage of up to 4 months of operator, laboratory, and on-line sensor data. The control programs were developed by IBM and the Pilot Plant Staff from analog or manual data and were applied to physical-chemical operations in two separate treatment systems: a physical-chemical system treating raw wastewater and a three-stage activated sludge system treating primary effluent.

Three unit processes of the physical-chemical system--lime clarification, recarbonation, and breakpoint chlorination--were initially selected for the computer control because the chemistry of the processes was sufficiently defined to permit process modeling and development of control algorithms. After development of the algorithms, digital control was successfully applied to the physical-chemical system. The algorithms in the physical-chemical system controlled sludge wasting and lime dosing in lime clarification, CO_2 and $FeCl_3$ dosing in recarbonation, and sodium hydroxide and chlorine dosing in breakpoint chlorination. Digital control was next applied to physical-chemical operations in the modified aeration, nitrification, and denitrification stages of the biological system. The algorithms controlled the alum dosing and D.O. in modified aeration, the lime dosing for pH control in nitrification, and the CH_3OH and alum dosing in denitrification.

In short term comparisons between digital, manual and analog control, data indicated digital control was a viable alternative to the manual and analog control approach. The digital process responded satisfactorily to gradual and step changes in flow and wastewater substrate concentrations. Both treatment systems under digital control produced 90 percent or more removals of nitrogen, phosphorus, and organics. Although these tests did not reveal any significant differences in system performance under the various control approaches, the digital control produced the smallest pH and chemical feed variation. Long term full-scale operation is required to statistically compare the effectiveness of automated versus manual control approaches for maintaining product quality and minimizing the chemical dosages.

This report was submitted in partial fulfillment of contract #68-01-0162 by the Government of the District of Columbia, Department of Environmental Services under the sponsorship of the U.S. Environmenta Protection Agency. This report covers an experimental period from December 1972 to December 1974.

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SECTION 1

INTRODUCTION

The Municipal Environmental Research Laboratory, Cincinnati, Ohio, and the District of Columbia Department of Environmental Services (DES), conducted pilot studies of advanced wastewater treatment of municipal wastewater at the Environmental Protection Agency - District of Columbia (EPA-DC) Pilot Plant. The pilot work evolved into studies of two basic treatment approaches; one approach consists of physical-chemical processes; the other, of advanced biochemical processes.

The unit processes within these approaches have been combined into various treatment systems able to remove carbon, phosphorous, and nitrogen from wastewater. The unit processes may be represented by two basic treatment systems, physical-chemical treatment of raw wastewater[1] and three-stage activated sludge treatment[2] of primary effluent. The pilot studies have provided design data while demonstrating water quality and systems reliability.

Automated process control and automatic data acquisition represented an important part of the research effort. The stringent objectives of product quality sought from the advanced systems mandated good process monitoring and operations.

The DES and EPA engaged International Business Machines Corporation (IBM) to provide a flexible, sensor-based, computer system for research on data acquisition, alarm monitoring, and process control of the various advanced wastewater treatment systems in the pilot plant.

The principal goal of the study was the development of digital algorithms to control various processes and operations in the physical-chemical three-stage activated sludge systems. In cooperation with the pilot plant staff, IBM developed[3] the computer-control programs for the physical-chemical system from analog and manual data provided by the pilot plant staff testing and evaluation of the digital control system was performed by the pilot plant staff after completion of the software. Subsequent software for the physical-chemical operations in the biological system were developed and tested by the pilot plant staff.

SECTION 2

CONCLUSIONS

The operation of physical-chemical and selected processes within the three-stage activated sludge systems under digital control represented the first successful digital computer control of wastewater treatment systems for the removal of organics, phosphorus, and nitrogen. The computer operated physical-chemical and advanced biological systems produced more than 95 percent removal of organics, 98 percent removal of phosphorus and 90 percent removal of the total nitrogen. The brief performance studies, however, did not reveal any significant difference in the performance of physical-chemical treatment under manual, analog or digital control or the three-stage activated sludge treatment under manual-analog or digital control.

The successful development of digital control in this study employed different approaches in the design of twelve control algorithms for the two treatment systems. In the physical-chemical system, three control loops employed flow proportional (feed-forward) control algorithms for sludge wasting from both lime clarification and recarbonation and for $FeCl_3$ addition in recarbonation. The lime and CO_2 feeds in the clarification process used flow-proportional (feed-forward) proportional-integral (feedback from pH error) algorithms. The digital control of breakpoint chlorination (Cl_2 and pH) employed a digital model of manual operation. Generally, the model provided satisfactory control of the complex process with the exception that large step changes in flow produced slow control recovery.

In the three-stage activated sludge system, three control loops also employed flow-proportional control algorithms for $FeCl_3$ addition in modified aeration and methanol and alum addition in denitrification. A mass proportional (feed-forward) control algorithm using nitrate concentration and process flow was developed as an alternate control strategy for methanol addition. With little diurnal variation in the nitrate concentration, the mass proportional algorithm did not exhibit any advantage over the flow-proportional for control of methanol addition. The digital control of dissolved oxygen in modified aeration and the pH in nitrification employed flow-proportional proportional-integral algorithms using the D.O. or pH error for feed-back. Abrupt changes in flow or in reactor solids concentrations produced oscillation in the D.O. control loop. Reducing the process gain and filtering the signal from the D.O. sensor produced effective control.

The digital control usually produced the smallest variation from control setpoint. While the short performance tests of this study did not reveal significant process quality or chemical consumption differences between

control methods, the improved control to setpoint in the digital approach indicated a potential for minimizing chemical consumption.

The computer exhibited a gradually increasing down time and eventually failed. Corrosion of the electrical terminals within the computer revealed a need for protecting the computer from the corroding atmosphere of the wastewater treatment plant.

SECTION 3

RECOMMENDATIONS

To fully assess and compare the capabilities of analog, digital, and manual control approaches for continuous production of appropriate quality water, full scale demonstrations should be supported. Long-term operation, with careful data acquisition is needed to assess the statistical effectiveness of the control approaches for minimizing the chemical and energy consumption and for increasing systems reliability.

Existing sensors for measurement of organics, phosphorous and nitrogen, should be improved for full time on line monitoring. The improvements needed include reduction of lag time, reduced maintenance and improved precision and sensitivity.

Long term operation is needed to develop experience data on maintenance of process sensors and control equipment within the wastewater plant environment.

If automated control technology is the answer to reliable product quality, training manuals should be prepared to provide the knowledge necessary for the operation and maintenance of these control systems.

Finally specification on sensing devices should be developed to reduce control system failures through improper selection of sensors.

SECTION 4

EXPERIMENTAL SYSTEMS

PHYSICAL-CHEMICAL TREATMENT

In the pilot studies, the basic physical-chemical system (Figure 1) consists of screening, two-stage (high pH) lime precipitation with recarbonation, dual-media filtration, breakpoint chlorination, and downflow granular carbon adsorption. The complete system was designed for a nominal capacity of 189 m^3/day (50,000 gpd) with a flow controller which could impress a diurnal variation of 4:1 maximum to minimum flow.

In the first stage of the lime precipitation process, raw wastewater, powdered CaO at a dosage of approximately 300 mg/l, and recycled solids were rapidly mixed and then flocculated in a turbine mixed flocculator. The lime increased the wastewater pH to approximately 11.5 and precipitated bicarbonate, phosphate, and magnesium ions from the water. The magnesium hydroxide that was formed at the high pH flocculated the organic solids and mineral precipitates which were removed after flocculation in a rectangular settler.

The limed water, after sedimentation, flowed through an open channel to recarbonation, where carbon dioxide was added in a turbine mixed recarbonation tank. The CO_2 reduced the wastewater pH from 11.5 to approximately 9.5 and precipated the excess calcium ions added in the liming stage. Five mg/l of ferric ions were also added in the recarbonation tank to form the flocculant $Fe(OH)_3$. The water was flocculated in a turbine mixed flocculation basin and then settled.

In each stage of the two-stage clarification process, settled solids were recycled from the bottom of the settler at a flow rate equal to 10 percent (empirically determined) of the average influent flow to the reactor to provide nuclei for chemical precipitation. The solids balances in the slurry pools of the settlers were maintained by wasting solids at a flow rate equal to approximately 1.5 percent of the influent flow.

The overflow from the second-stage settler was pumped to a distribution box ahead of two filters. It then flowed by gravity through the dual-media filters to remove the residual particulates. Each filter was packed with 0.61m (24 inches) of 0.5 mm coal above 0.15 m (six inches) of 0.45 mm sand.

After filtration, the wastewater was chlorinated to oxidize the ammonia to nitrogen gas. In this reaction, the chlorine formed hypochlorous acid which oxidized the ammonia first to monochloramine and then to N_2 gas. A base was required to neutralize the HCl produced by the chlorination reactions.

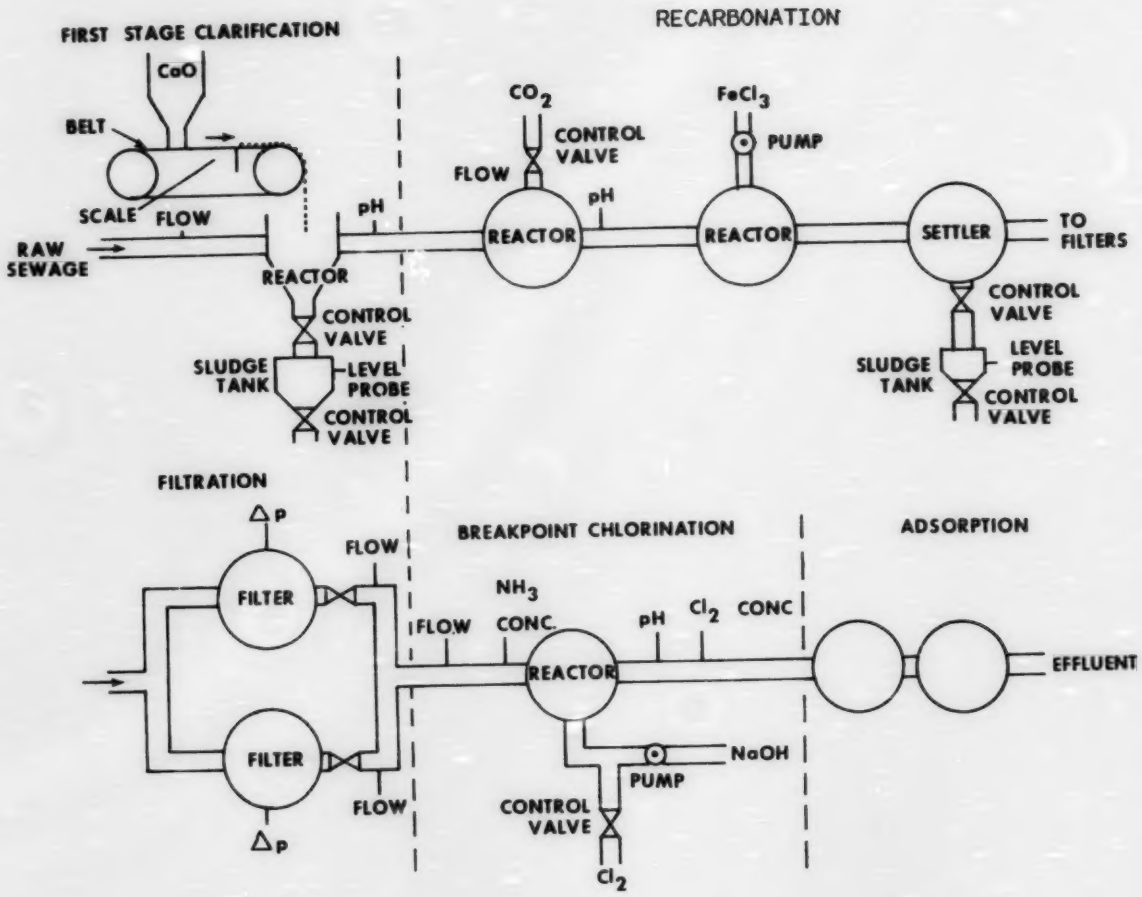

Figure 1. EPA-DC pilot plant "physical-chemical system."

The breakpoint occurred in the reaction when the NH_3-N concentration was reduced to zero. At this point, free available chlorine was detected and the total residual chlorine was minimized.

The chlorine demand depended upon the ammonia and nonammonia chlorine demand and the desired amount of free residual chlorine in the wastewater. For the Washington, D.C. lime clarified raw wastewater, the $Cl:NH_3$-N dosage weight ratio was approximately 9:1. Breakpoint chlorination was maintained using a Kenics static mixer with 21 mixing elements and 1.6 seconds average detention time. The rapid mixing, a controlled pH of approximately pH 7 and a low free residual chlorine concentration which favors oxidation to N_2 minimized the undesirable production of nitrogen trichloride and nitrate.

After a 1-minute chlorine contact time, the flow from the chlorination process was pumped through downflow granular carbon columns with a detention time of approximately 30 minutes to remove most of the soluble residual organics. The carbon also removed the residual total chlorine from the breakpoint process.

The waste solids from the physical-chemical treatment system were thickened and classified with a centrifuge into carbonate (centrifuge cake) and non-carbonate solids (centrate). The centrifuge cake was recalcined to produce CaO and CO_2, for reuse in the clarification process. The centrate was dewatered by pressure filtration. These solids handling options while tested in the pilot plant were not routinely operated at the pilot scale and were not automated. During the automation study, recalcined lime, however, was used with digital pH control operating the lime feeding system..

THREE-STATE ACTIVATED SLUDGE TREATMENT

The basic three-stage activated sludge system (Figure 2) consisted of modified aeration, nitrification, denitrification, and filtration. The system was designed for a nominal capacity of 189 m^3/day (50,000 gpd) with a flow controller which impressed a diurnal variation of 2.1:1 minimum to maximum flow. Primary effluent was pumped to the modified aeration reactor which consisted of three completely mixed passes of equal size. Compressed air was supplied through perforated PVC pipe diffusers and the dissolved oxygen levels in each stage were manually maintained between 1 and 2 mg/l. Ferric chloride was added to the third pass of the reactor. The effluent was discharged to a circular peripheral feed clarifier. Recycle solids were returned at a constant percentage of influent flow.

The effluent from the modified aeration clarifier was pumped to the second biological system for nitrification. The nitrification reactor consisted of four complete mix passes operated in series. Air was supplied independently to each pass and the dissolved oxygen was manually maintained between 0.5 and 4.0 mg/l. A dry lime feeder was located above the first pass and lime was automatically (analog) fed to maintain the desired effluent pH. The effluent from the reactor flowed to a circular center-feed clarifer and recycle solids were returned from the clarifier to the reactor at a constant

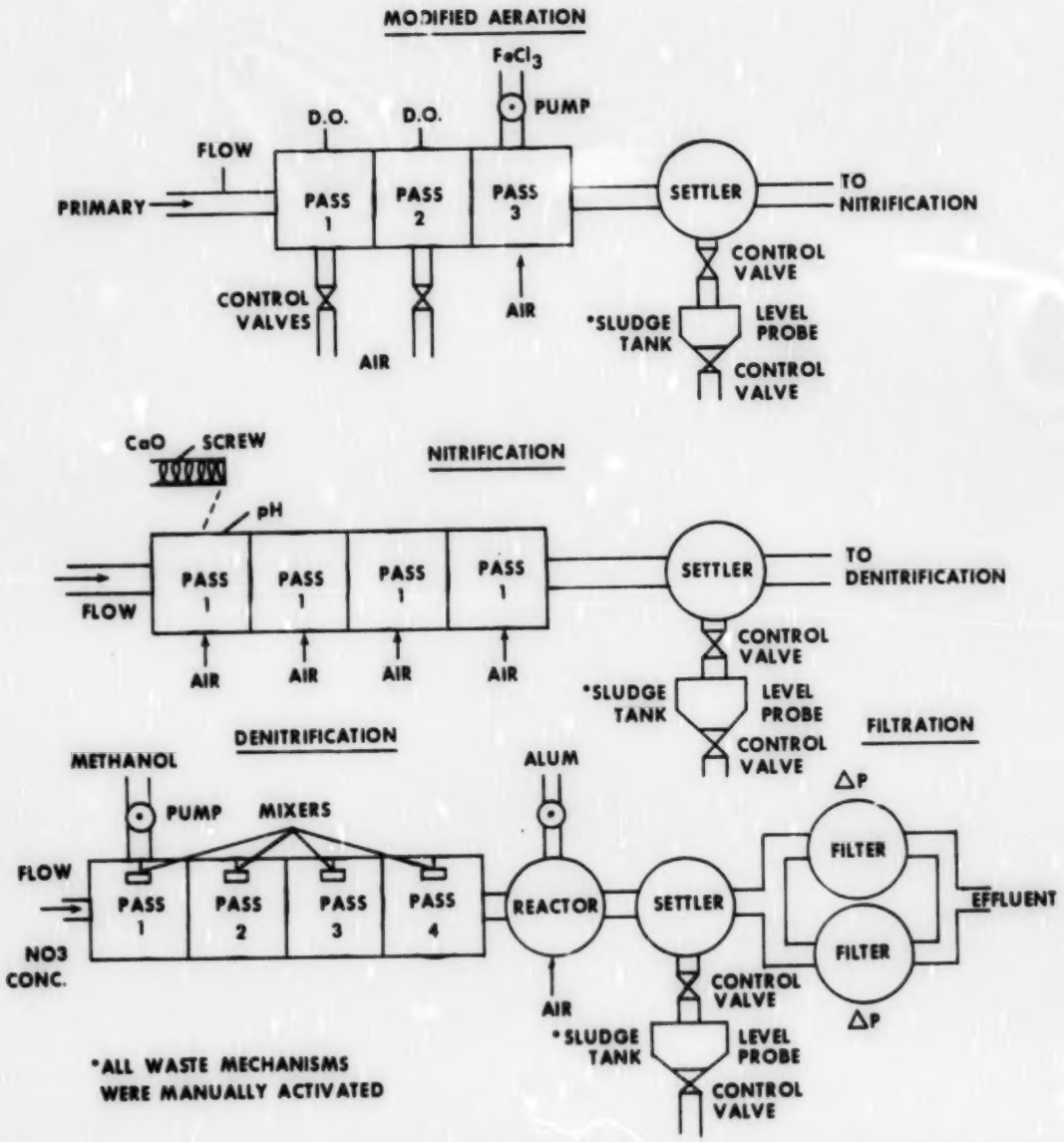

Figure 2. EPA-DC pilot plant "three-stage activated sludge system."

rate. Methanol was pumped to the effluent from the nitrification clarifier and the process flow as sent to the denitrification reactor.

The denitrification reactor consisted of four, covered, mechanically stirred tanks of equal size operated in series. The tanks were covered to exclude oxygen transfer from the air. The effluent from the denitrification reactor then flowed directly into a singly, aerated, completely mixed chamber in order to strip nitrogen gas from the water and to oxidize any excess methanol leaving the denitrification reactor. Alum was also added to this chamber for residual phosphorus removal and solids flocculation. Following aeration, the effluent flowed to a circular center-feed clarifier. Recycle solids were returned from the clarifier to the denitrification reactor at a constant rate of flow.

Effluent from the denitrification clarifier flowed to a splitter box, where it was equally divided before flowing to a dual-media and multi-media filter. The dual-media filter consisted of 0.30 m (12 inches) of 0.6 to 0.7 mm sand overlain by 0.61 m (24 inches) of 1.2 to 1.4 mm coal. The multi-media filter consisted of 0.08 m (3 inches) of 0.2 to 0.35 mm ilmenite overlain by 0.23 (9 inches) of 0.4 to 0.5 mm sand overlain by 0.2 m (8 inches) of 1.0 to 1.1 mm coal overlain by 0.41 m (16 inches) of 1.5 to 1.6 mm coal. Differential pressure readings were taken at various bed depths, and the filters were backwashed either when the total pressure drop reached 3.0 m (120 inches) or after 24 hours even though the pressure drop had not yet been attained.

COMPUTER SYSTEM HARDWARE

To implement the digital control system for the control of the physical chemical and three-stage activated sludge treatment processes, an IBM System/7 was used. This modular, sensor-based digital computer with interrupt capability was also used for data acquisition. The hardware consisted of one processor module including a 16K monolithic memory with 400 ns cycle time, two input/output (I/O) modules, a disc storage module, with 1.23 megawords of storage capacity, and one operator station (Figure 3). The computer was located in an air-conditioned office within the pilot plant building. The multifunction I/O modules provided the required analog and digital inputs and outputs. Some 60 analog inputs points, including the analog inputs for process control, were monitored by the computer representing measurements for pH, flow, pressure, sludge density, temperature and online analysis of nitrate, ammonia, and free chlorine concentrations. Thirty-two of these analog points were read once per second and their values smoothed for process control.

Digital signals from switches and inputs from pressure sensors in receiver tanks, hydraulic levels, etc., was handled through 35 digital input points. For one group of 16 inputs, an interrupt feature was included; this feature allows comparison of the status of this group bit-by-bit against a 16-bit reference register. If the status of one or more bits did not agree with the register bits, an interrupt could be initiated. The operator

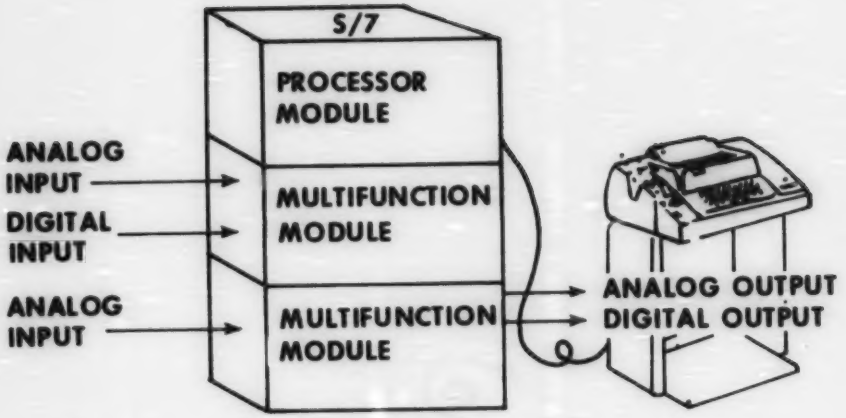

Figure 3. IBM System/7 configuration.

communicated with the computer through the keyboard and the printer on the operator station. Paper tape reader and punch were also provided on the operator station.

For the data acquisition task, all 60 analog and 35 digital input points were scanned periodically. The data was either converted to engineering units and punched on paper tape at the operator station for further processing (data reduction, report generation, etc.) or the data was stored on the disc.

The disc was used for program storage as well as data storage. Process control and data handling programs were transferred to the processor module at a desired frequency or on request, preformed and returned to disk storage (Figure 4). The programs operated in either of two areas dependent on their function and residence time. The data storage allowed for the automatic collection, hourly averaging and disc storage of up to 128 sensor inputs or automatically computed values. The disc allowed up to 128 operator entered values gathered as often as once per hour. It also allowed the manual entry of up to 16 laboratory analyses per day taken from up to 10 sample points per unit process on up to 12 unit processes. This amounted to a total of 8,064 inputs per day for four months.

The previously described analog and digital input points were also used for alarm monitoring. If process variables were out of an operated selected range or operations were not performed properly, the operator was notified by an audio/visual alarm signal.

Data Acquisition

The data acquisition and storage system of the System 7 accepted data of four different categories; continuous sensor read by the computers, calculations made by the computer, operator readings and analyses, and laboratory analyses.

Each sample was accessed by a four digit alphanumeric identification code. The first character was a letter which represented the unit process. The second character was a number between "0" and "9" which represented the sample point within the unit process. The third and fourth characters were either numbers or letters and represented the type of sample made (for example, "pH" and "DO" represented pH and dissolved oxygen, respectively).

Continuous Sensors--

Process monitoring equipment located throughout the pilot plant transmitted information electronically to the computer. The sensors included flowmeters, dissolved oxygen analyzers, pH probes, temperature transmitters, suspended solids meters and wet chemical analyzers measuring ammonia, free residual chlorine, and nitrite-nitrate. The 60 individual sensors were read every 2 minutes, linearized where necessary, converted to engineering units, averaged for one hour and stored in the disc file according to the sample identification code, month, day and hour.

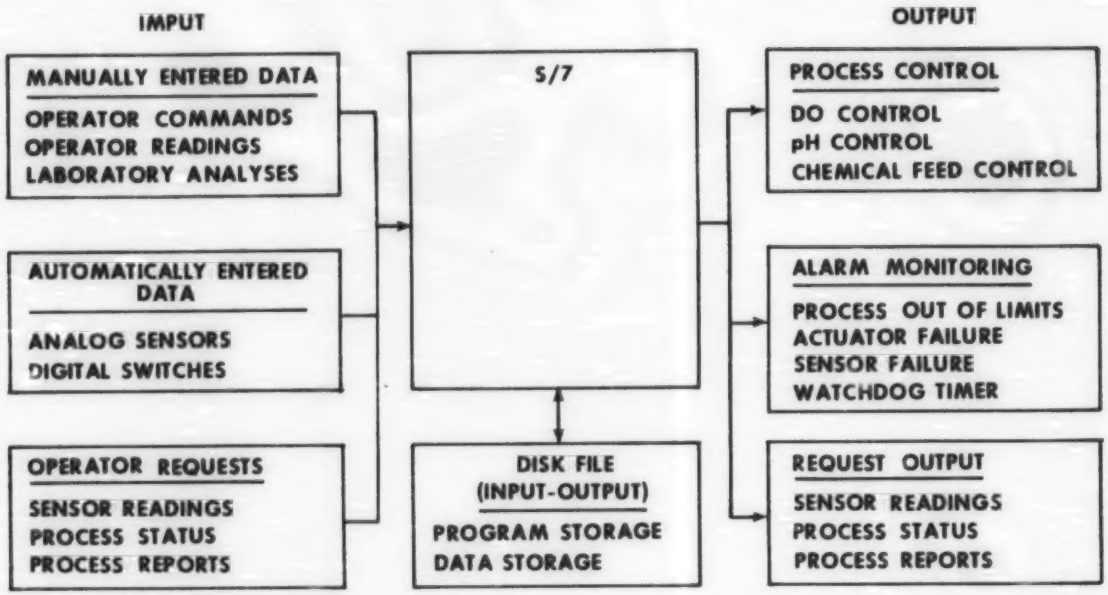

Figure 4. Information transfer system.

Computed Values--

The computer automatically logged information concerning the control of the processes such as chemical usage rates, dosage, etc. These values were averaged for an hour and stored in the disc file, again according to the identification code, month, day and hour.

Operator Data--

The operators on a regular schedule read non-transmitting devices, performed basic analyses on process samples such as alkalinity and turbidities and measured process variables such as pH and DO where continuous sensors were not installed. Up to 128 separate measurements read up to once per hour were then manually entered through the operator station into the computer. To speed up the entering process and to minimize typographical errors, the operator gave the computer the date and time of sample readings whereupon the computer initiated an automatic quizzing process. Beginning with the first sample on the operator log sheet, the computer pointed out the identification code to which the operator responded by typing only the numerals and decimal point. The computer then typed the identification code of the next sequential item on the operator's log and continued this process either until the entry was complete or the operator terminated the process.

The storage and data acquisition capabilities of the system were used to gather data for algorithm development. Programs were also developed for report generation but never implemented.

SECTION 5

CONTROL APPROACH

CONTROL SYSTEMS

Three processes of each system; lime clarification, recarbonation, and breakpoint chlorination in the physical-chemical system, and modified aeration, nitrification and denitrification in the three-stage activated sludge system were selected for the application of computer control (Tables 1 and 2). Only physical-chemical processes or operations were controlled in the three-stage activated sludge system.

The digital process control system consisted of eleven independent control functions (Tables 1 and 2). The process information required by these functions was presented to the computer in the form of analog inputs and two discrete inputs. Analog and digital outputs from the computer were used for control. The analog inputs were sampled by the computer once per second and then processed by a low-pass digital filter of the form commonly referred to as an exponential filter. The mathematical representation of the filter is:

$$C(nT) = (1-\alpha)C'(nT) + \alpha C\{(n-1)T\} \quad (1)$$

where $C(nT)$ = smoothed value of measured process variable at the n^{th} sample time.

$C'(nT)$ = measured value of process variable at the n^{th} sample time.

T = sample period.

α = parameter which determines the frequency discrimination characteristics of the filter $0<\alpha<1$.

The control algorithms made use of only the filtered or smoothed values of the measured process variables. The two discrete inputs were interfaced with the computer such that an ON signaled by either of the inputs caused any activity in the computer to be interrupted. The computer was then able to take the appropriate action immediately.

The control equipment also included an electropneumatic logic network, not linked to the computer. The logic network was based on time, level and

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TABLE 1. PHYSICAL-CHEMICAL CONTROL SYSTEM

Stage	Control Objective	Control Variable	Sensors	Actuators
Lime clarification	pH setpoint range: 11.3-12.0	CaO Feed range: 0-24 lb/hr	pH assembly Magnetic flow meter	Gravimetric feeder
	Sludge wasting range: 0.5-2.5% of flow	Volume	Magnetic flow meter Level switch	Electropneumatic ball valve
Recarbonation	pH setpoint range: 9-9.8	CO_2 Feed range: 0-480 lb/hr	pH assembly Magnetic flow meter	Equal percentage valve
	Sludge wasting range: 0.5-2.5% of flow	Volume	Magnetic flow meter Level switch	Electropneumatic ball valve
	$FeCl_3$ dosage range: 0-10 mg/l	$FeCl_3$ Feed	Magnetic flow meter	Peristaltic pump
Breakpoint chlorination	Free Cl_2 residual range: 3-5 mg/l pH setpoint range: 7.1-7.5	Cl_2 Feed range: 0-120 lb/day	Magnetic flow meter Autoanalyzers for Cl_2 and NH_3	V notch Chlorinator
		NaOH Feed range: 0-6.8 liter/min. (8.5%) NaOH by weight	pH assembly Magnetic flow meter	Positive displacement pump

TABLE 2. THREE-STAGE ACTIVATED SLUDGE CONTROL SYSTEMS

Stage	Control Objective	Control Variable	Sensors	Actuators
Modified Aeration	$FeCl_3$ dosage range: 1-1.2 times Phosphorus Conc.	$FeCl_3$ Feed	Magnetic flow meter	Positive Displacement Pump
	D.O. Concentration range: 1-2 mg/l	Air Flow	Magnetic flow meter D.O. Meter	Linear Throttling Value
Nitrification	pH Set Point range: 7.0-7.5	CaO Feed	Magnetic flow meter pH Assembly	Gravimetric Feeder
Denitrification	CH_3OH dosage range: 3.7-4.6 times the Nitrate Conc.	CH_3OH Feed	Magnetic flow meter Autoanalyzer for Nitrate	Positive Displacement Pump
	Alum dosage range: 38.7-46.9 mg/l	Alum Feed	Magnetic flow meter	Positive Displacement Pump

differential pressure to automatically control backwashing cycles of the filters in both treatment systems and the carbon columns in physical-chemical systems.

The computer indirectly controlled the water quality from both treatment systems by minimizing the pH error in lime clarification, recarbonation, breakpoint chlorination, and nitrification; by controlling the dosage of $FeCl_3$ in recarbonation and modified aeration, the dissolved oxygen concentration in modified aeration, the dosage of CH_3OH and alum in denitrification, the free residual Cl_2 concentration in breakpoint chlorination, and finally by controlling the amount of sludge wasted from lime clarification.

ALGORITHM DEVELOPMENT

The control objectives in Tables 1 and 2 require control algorithms ranging from the simple feedforward loops to complex feedback/feedforward combinations. The control algorithms in some cases included more than one principal control relationship and supporting computer control statement. The actual programs were written in the machine language of the System/7. The principal control relationships and the computer control statements are described here. It should be noted that the equations are presented in general form. The constants or empirical functions represented by symbol in the general form of the central algorithm must be determined for each site specific application.

Sludge Wasting Control

The algorithms developed to provide regulation of lime sludge wasting used feedforward control only. The algorithm performed rectangular integration of the influent flow rate to obtain the volume (V_w) of influent to the physical-chemical system since the previous sludge wasting.

$$V_w = T\Sigma Q(nT) \qquad (2)$$

where T = interval of integration (sample period)

$Q(nT)$ = wastewater flow rate.

When a percentage of this integrated volume equalled or exceeded the volume of the sludge receiver tank, the algorithm commanded the sludge receive tank drain valve to close and the sludge wasting valve to open. A level probe on the sludge receiver tank signaled (discrete input) the computer when the wasting operation was complete, and the algorithm subsequently commanded the sludge wasting valve to close and the receiver tank drain valve to open. The sludge receiver tank volumes for both lime clarification and recarbonation, as well as the waste percentages for each unit process, could be specified by the process operator. The actuator signal from the computer was:

$$\text{Actuator signal} = \begin{cases} \text{ON} & \alpha Vw > VRT \\ \text{OFF} & VRT \text{ is full} \end{cases} \quad (3)$$

where VRT = volume of sludge receiver tank.

Chemical Addition Control

The development of the algorithm for regulation of the $FeCl_3$ dosage to lime clarification and modified aeration, and CH_3OH and alum dosages to denitrification, paralleled that of the sludge wasting algorithm as a feedforward control was employed. This feedforward algorithm governed the percentage of time that the peristaltic (set rate with variable time) pump dispensing the $FeCl_3$, CH_3OH, alum, etc., remained activated. The algorithm performed the following calculation once per minute to determine the ON time in seconds per minute:

$$ON = \cdot \frac{60\ V_1\ Q(nt)}{V_2\ V_3} \quad (4)$$

where V_1 = desired dosage (mg/l of wastewater)

V_2 = concentration of chemical solution (mg/ml of soln.)

V_3 = pump rate (ml/min).

The computer actuator signal to the pump was on or off, based on the ON time. The computer control of the chemical solution feed rate was also evaluated for two other types of pumps: a set-stroke with variable speed and a set speed with variable stroke. The pumps were compared for reliability and performance. All of these pumps were designed for positive displacement and head pressure insensitivity in their normal operating ranges. However, the feed rates of all three pumps varied with the level of the chemical storage tank, i.e. with suction head pressure. With a constant head chemical storage tank, the variable on-time pump performed quite well. It was necessary for the variable speed pump to incorporate an empirical table look-up routine in the computer program to account for a non-linear relationship between the pump rate and the input signal. The computer by interpolation selected the speed of the pump. When operated with a constant head feed tank, the pump then showed good performance and repeatability. The variable stroke pump presented the greatest difficulties and never performed satisfactorily. In addition to its suction head pressure sensitivity, the pump showed nonlinearity and poor repeatability throughout its operating range. From a material balance, the control algorithm for the variable speed pump was:

$$V_3 = \frac{V_1}{V_2} Q(nt) \quad (5)$$

The relationship for the computer actuator signal was:

$$\text{Actuator signal} = f_{FE} V_3 \quad (6)$$

where f_{FE} = empirical functional relationship between V_3 and the final element, the pump output.

Effluent pH Control

The basic structure of the algorithms developed to regulate the effluent pH of the lime clarification and recarbonation process is presented in Figure 5. The control loop employed pH error for feedback and process flow for feedforward control. The approach taken in the design of the Proportional Integral (PI) Controller for feedback control was to:

1. Hypothesize a mathematical process model structure;
2. Obtain step response data on the processes throughout the range of process operating points;
3. Develop the process model;
4. Mathematically derive a deadbeat control law for the process model where deadbeat control is designed to reduce the pH error to zero in one sample time.

The process models developed for the lime feed and CO_2 feed were represented as first order linear differential equations with lumped time invariant parameters. As was shown (3), the deadbeat control law for this model structure took on the same structure as that of the familiar digital PI control law.

$$D(nT) = \frac{1}{P(nT)} \left\{ \frac{e^{-T/\tau}}{1 - e^{-T/\tau}} \right\} E(nT) + \frac{1}{P(nT)} \Sigma E(nT) \quad (7)$$

where $D(nT)$ = required chemical dosage computed by the PI controller at the n^{th} control instant

$P(nT)$ = process gain computed at the n^{th} control instant

$E(nT)$ = difference between the desired pH (set point) and the smoothed value of the measured pH

τ = time constant of the process model

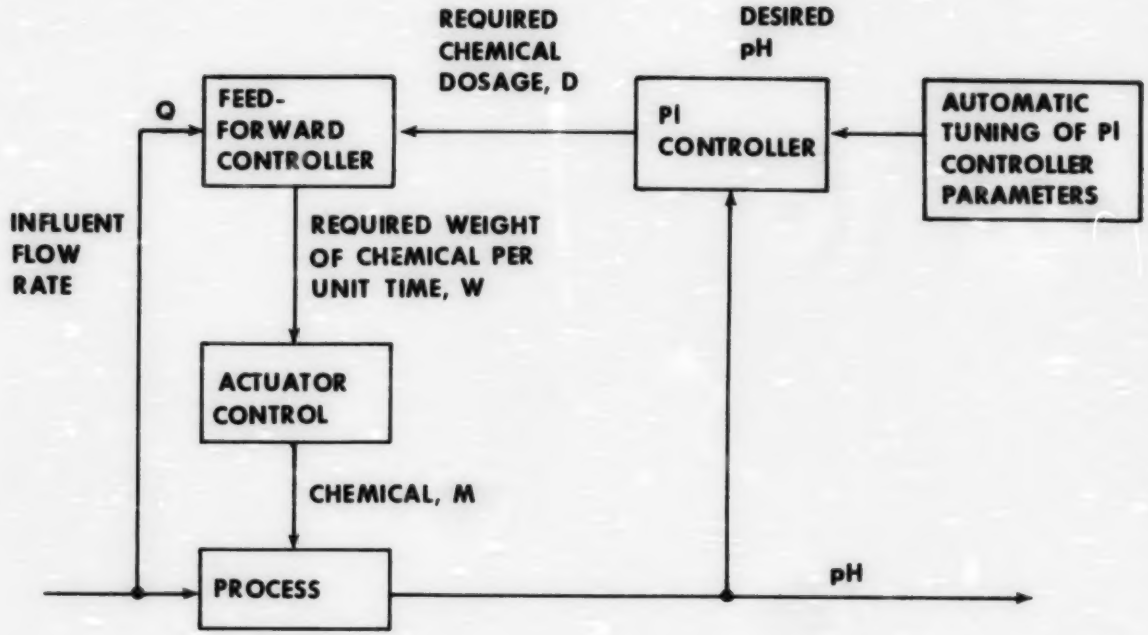

Figure 5. Control algorithm structure for effluent pH regulation of the lime clarification recarbonation and nitrification subsystems.

T = control period (T = 60 seconds for the lime clarification and lime addition in nitrification; T = 15 seconds for recarbonation)

e = a constant = 2.7183.

The set of step response curves associated with the two unit processes were used to obtain steady-state process gain curves which gave the relationship between the effluent pH and the chemical dosage being introduced to the process. These two empirically derived gain curves were then approximated by analytical functions.

$$P(nT) = \frac{\beta pH(nT)}{|n\alpha - [|n(\alpha - pH(nT)]}, \quad \text{gain function for the lime clarification process and for lime addition in nitrification.} \tag{8}$$

$$P(nT) = \frac{pH(nT)}{\beta\, 2\, [|n\alpha - |n\, pH(nT)]}, \quad \text{gain function for the recarbonation process} \tag{9}$$

where α, β = constants

$pH(nT)$ = smoothed value of pH at the n^{th} control instant.

The constants in Equations 6 and 7 were selected to reduce the process error to zero in one sample time.

The analytical functions thus developed were used in the control algorithms to compensate the PI controller parameters for the nonlinear process gain characteristics. This parameter tuning function produced near uniform algorithm performance throughout the design range of operating set points.

Feedforward control was added by forming the product of smoothed influent flow rate and the feedback output of the PI controller--the required chemical dosage (weight of chemical per unit volume of wastewater)--to compute the weight of lime or CO_2 to be added, W(nT):

$$W(nT) = D(nT)\ \{Q(nT)\}. \tag{10}$$

The actuator control for the lime clarification process consisted of a second feedback loop which governs the percentage of time that the gravimetric feeder was operated (ON/OFF) during the period of time between subsequent control actions (one minute, in this case). The delivered weight of CaO per minute, M(nT), is measured and time integrated (totalized). When the totalized weight of CaO equals that required by the output of the feedforward controller, the CaO feeder is turned off.

$$\text{Actuator Signal} = \begin{cases} \text{ON}, & \sum_{t=0}^{n} M(nT) > W(nT) \\ \text{OFF, otherwise} \end{cases} \quad (11)$$

Actuator control for the recarbonation process was implemented differently, where an equal percentage valve was used to control the flow of CO_2 gas. The nonlinear valve characteristics were empirically determined. The characteristics describing the functional relationship between the CO_2 flow rate and actuator signal issued by the computer were implemented in the control algorithm as a table look up and used to develop the correct actuator signal in response to output of the feedforward controller--the required CO_2 flow rate. Thus the computer actuator signal was:

$$\text{Actuator Signal} = f_{FE}\, W(nT) \quad (12)$$

where f_{FE} = empirical functional relationship between valve CO_2 flow and W(nT).

Actuator control of the pH in nitrification was similar to the actuator control for lime clarification except that the capability for control by time integrated weight was not available. Dry lime was added by activating a screw feeder at constant feed rate for a number of seconds each minute to meet the pH control requirements. The actuator signal was:

$$\text{Actuator signal} = \begin{cases} \text{ON}, & \geq a\, W(nT) \\ \text{OFF, otherwise} \end{cases} \quad (13)$$

where a = rate of CaO delivery, g/sec.

Breakpoint Chlorination Control

The initial planning for a breakpoint chlorination control algorithm called for the development of a steady-state control algorithm to achieve noninteractive regulation of free residual chlorine and effluent pH. It soon became apparent, however, that the quantity and quality of process response data required to develop the intended control strategy was not likely to be forthcoming under manual control of the process.

The process was further complicated by the large Cl_2 dosage (150 mg/l) for breakpoint and the small residual (4 ± 2 mg/l) required for control. For effective control, the control hardware evolved to the use of two actuators, a large chlorinator supplying the major portion of the feedforward dosage and a small chlorinator controlled by feedback to complete the breakpoint and control the free residual chlorine.

A decision was made that a different control strategy must be designed and implemented. The intent was to provide a digital control strategy that could be used as a basis for collecting the process data necessary to model the breakpoint process.

The algorithm employed a dead band control strategy with a logic program and may be thought of as the implementation of the procedures that a process operator might employ in manually controlling the process. The control functions were as follows:

1. Feedforward control of Cl_2 and NaOH to compensate for variations in wastewater flow rate and ammonia concentrations were done every five seconds. The new dosages were computed from old dosages by adding linear incremental corrections to the old dosages.

2. Feedback control of Cl_2 and NaOH to correct for out of limit pH and Cl_2 concentrations were done in a routine which was entered on either a 5-second or a 5-minute cycle. When entered, the routine checked first the effluent pH and second the free residual chlorine.

Due to the influence of pH on the analysis of free Cl_2, chlorine dosage adjustments could not be made when the process pH was less than 6.6 or greater than 7.8.

The logic sequence to control the breakpoint process was as follows:

- Read pH.
- If pH was within dead band (± 0.2 pH units around setpoint) limits, read free Cl_2 residual. If free Cl_2 was within dead band limits (± 2 mg/l of setpoint), wait five seconds and reenter logic sequence.
- If pH was outside dead band limits but inside alarm limits (< 6.6 or > 7.8), read free Cl_2 residual. If free Cl_2 residual is within dead band limits, adjust NaOH dosage. Wait five minutes and reenter logic sequence.
- If pH was within dead band limits, read free Cl_2 residual. If free Cl_2 residual was outside dead band limit, adjust Cl_2 dosage and maintain Cl_2/NaOH ratio. Wait five minutes and reenter logic sequence.
- If pH was outside dead band limits, but inside alarm limits, read free Cl_2 residual. If free Cl_2 residual was also outside of dead band limits, determine the necessary changes in the Cl_2/NaOH dosage ratio and adjust the Cl_2 and NaOH dosages. Wait five minutes and reenter logic sequence.

The equations for accomplishing the above control actions were:

$$D_1(nT) = \underset{\text{feedback increment}}{a\ \{\text{pH set} - \text{pH}(nT)\}} + D_1\ \{(n-1)T\} + b\ \{[D_2(nT) + D_3(nT)] - [D_2(n-1)T + D_3(n-1)T]\} \quad (14)$$

$$D_2(nT) = c\ \{Cl_2\ \text{set} - Cl_2(nT)\}\ (\text{feedback increment}) + D_2\ \{(n-1)T\} \quad (15)$$

$$D_3(nT) = d\ \{A(nT) - A\ \{(n-1)T\}\}\ (\text{feedforward increment}) + D_3\ \{(n-1)T\} \quad (16)$$

where $D_1(nT)$, $D_1\{(n-1)T\}$ = required caustic dosage calculated at the n^{th} and $(n-1)^{th}$ control instant

$D_2(nT)$, $D_2\{(n-1)T\}$ = required feedback chlorine dosage (small chlorinator) calculated at the n^{th} and $(n-1)^{th}$ control instant

$D_3(nT)$, $D_3\{(n-1)T\}$ = required feedforward chlorine dosage (large chlorinator) at the n^{th} and $(n-1)^{th}$ control instant

pH set = desired value of effluent pH

pH(nT) = smoothed value of pH at the n^{th} control instant.

Cl_2 set = desired value of free residual chlorine concentration

$Cl_2(nT)$ = smoothed value of free residual chlorine at the n^{th} control instant

A(nT), A {(n-1)T} = smoothed value of ammonia concentration at the n^{th} control instant

a, b, c = proportionality constants for incremental feedback control of effluent pH and free residual chlorine

d = $Cl:NH_3$-N dosage ratio.

Feedforward control for influent flow rate variations was implemented as follows:

$$W_1(nT) = D_1(nT)\ Q\ (nT) \quad (17)$$

$$W_2(nT) = D_2(nT)\ Q\ (nT) \quad (18)$$

$$W_3(nT) = D_3(nT)\ Q\ (nT) \quad (19)$$

where $W_1(nT)$ = required amount of caustic per unit time

$W_2(nT)$ = required amount of feedforward chlorine per unit time

$W_3(nT)$ = required amount of feedback chlorine per unit of time

The actuators for the chlorine dosages were two V-notch chlorinators with linear output. For the caustic dosage, the actuator was a variable stroke positive displacement pump. The pump output was nonlinear with stroke and exhibited mechanical hystersis. The computer actuator signal for caustic dosage was:

$$\text{Actuator signal} = f_{FE}\, W_1(nT) \tag{20}$$

where f_{FE} = complex empirical function describing pump output with stroke

and for chlorine were:

$$\text{Actuator signal} = g\, W_2(nT) \tag{21}$$

$$\text{Actuator signal} = h\, W_3(nT) \tag{22}$$

where g, h = proportional constant for linear chlorinator output.

The algorithm satisfactorily controlled the complex breakpoint chlorination process but exhibited slow recovery responses for abrupt step changes in flow. Later after completion of the algorithm development for the three-stage activated sludge system, an attempt was made to improve breakpoint chlorination control. In that attempt, the pH in the breakpoint process was successfully controlled by the feedback PI controller (Equation 7) with a feedforward correction (proportioned to process flow). At the same time, the chlorine addition and residual free chlorine was successfully controlled by the output of an analog PI controller with the feedback error signal based on residual Cl_2 difference from setpoint coupled to an analog flow proportional output based upon process flow. While the approach was completely feasibile, the digital parallel of the analog Cl_2 controller was not completed.

Mass Proportional Control of CH_3OH

In denitrification, mass-proportional control was applied to the CH_3OH feed system. An autoanalyzer was used for continuous measurement of nitrite-nitrate concentration entering the denitrification stage. In the mass-proportional control, the measured concentration of nitrite-nitrate and the process flow rate were combined to determine the chemical feed rate. The mathematical description of this program was:

$$V_3 = \frac{V_1}{V_2}\, M\, Q(nT) \tag{23}$$

where V_3C = chemical pumping rate, ml/min

$Q(nT)$ = process flow, l/min

M = mass proportional ratio

V_1W = nitrite-nitrate concentration, mg/l

V_2I = concentration of methanol solution

The actuator was a variable speed pump and the computer actuator signal was:

$$\text{actuator signal} = f_{FE}\, V_3 \qquad (24)$$

where f_{FE} = empirical functional description of the feed element (input signal vs. ml/min).

This is visually represented in Figure 6.

Mass-proportional control of $FeCl_3$ addition to the final pass of modified aeration for phosphorus removal was also attempted. An autoanalyzer method to measure total phosphorus, however, produced a coating on the optical viewing element which required frequent cleaning (approximately every hour). This coating occurred in spit of settling and filtration of the sample prior to its passing through the optical viewer. The coating prevented the use of the sensor in the $FeCl_3$ mass-proportional feed control system.

Dissolved Oxygen Control

Dissolved oxygen control in the modified aeration process required continuous adjustment of the air flow rate to compensate for changes in the air requirements of the biological system. The air requirement was dependent on numerous factors. The amount of carbonaceous material and the number of biological organisms present in the reactor could change relatively rapidly. The oxygen consumption rate changed with variation in the influent concentration of carbonaceous material or with variation in the process flow. The system oxygen consumption rate also changed with variations in the recycle to process flow ratios. Sensors were not available for measuring continuously the suspended solids in the recycle flow or carbonaceous material in the influent process flow so feedforward information was limited to process and recycle flow. The exact relationship of process flow to air requirement was not known going into the study but was to be examined once dissolved oxygen control was established at steady-state conditions. Since it was expected that the maximum impact of disturbances would be felt in the first stage, dissolved oxygen control was attempted on the first two passes of the modified aeration stage.

The two passes were controlled totally independently of each other, both using automatic air throttling valves under direct digital control. The PI Controller with feedforward compensation was used by the computer and can be expressed mathematically by:

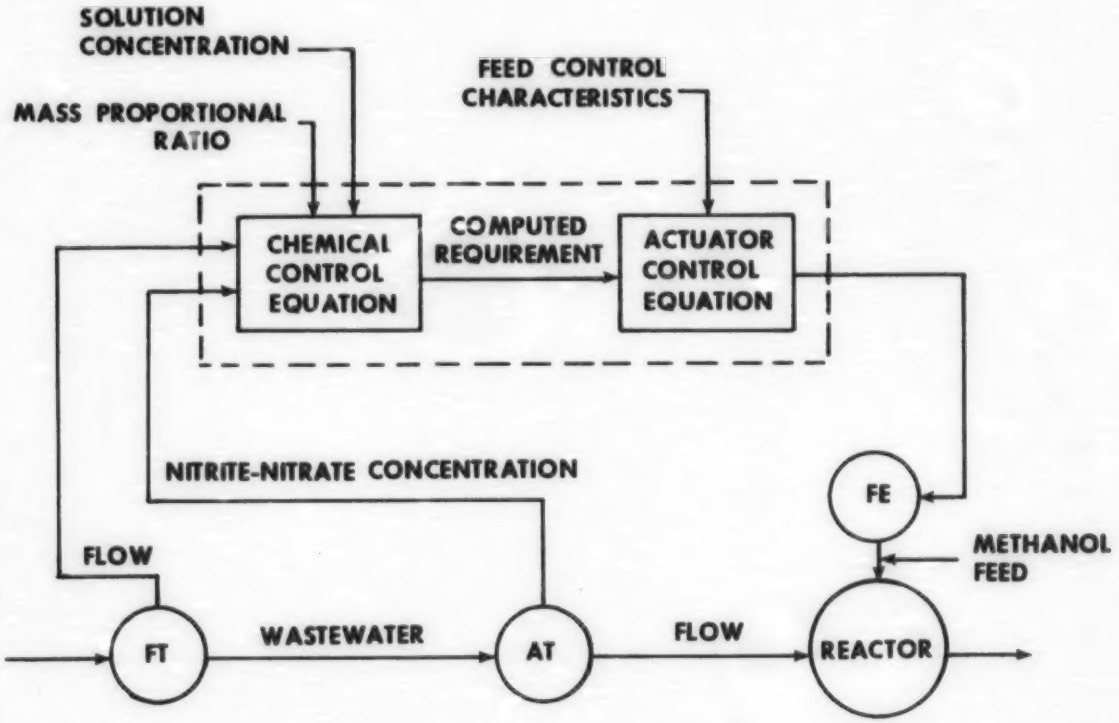

Figure 6. Mass proportional chemical feed control.

$$SCFM(nT) = \left\{\frac{1}{P_{DO}(nT)}\left[\frac{e^{-T/\tau}}{1-e^{-T/\tau}}\right] E_{DO}(nT) + \frac{1}{P_{DO}nT}\Sigma E_{DO}(nT)\right\} F(Q) \quad (25)$$

where $SCFM(nT)$ = required air rate computed by the controller at the n^{th} control instant

$P_{DO}(nT)$ = process gain computed at the n^{th} control instant

τ = time constant of the process model

T = control period ($T = 96$ seconds)

$E_{DO}(nT)$ = difference between the desired DO (set point) and the smoothed value of the measured DO

$F(Q)$ = feedforward correction based on process flow and raised during the study.

The empirical process gain was approximated by:

$$P_{DO(nT)} = \frac{B\ DO(nT)}{\ln SDO - \ln(SDO - DO\ nT)} \quad (26)$$

where SDO = the saturation DO level, mg/l

DO = the smoothed value of the dissolved oxygen concentration, mg/l.

The computer actuator signal to the control valve was:

$$\text{Actuator signal} = f_{FE}\ SCFM(nT) \quad (27)$$

where f_{FE} = empirical functional relationship between the air valve and SCFM(nT).

A visual representation of the control loop is shown in Figure 7. One of the problems encountered immediately was that the unsmoothed dissolved oxygen signal exhibited relatively large amplitude, high frequency flutter, ±0.3 mg/l within one second (see Figure 8). Thus, it was necessary to heavily dampen the signal for use in the control program [A Palo Alto, California, study also encountered this flutter and attributed it to eddies and varia-variations in dissolved oxygen passing by the membrane of the sensor (4)].

With the algorithm, the dissolved oxygen level was brought under satisfactory control for steady-state conditions. At that point, the process was again subjected to the stress of the diurnal flow pattern. Although control was maintained during the flow changes, the degree of control was reduced and therefore various feedforward flow compensation functions were tested. This flow compensation function was expressed as F(Q) in the control equation above. It was varied from linear to various non-linear relationships which empirical data suggested. Linear flow proportioning resulted in

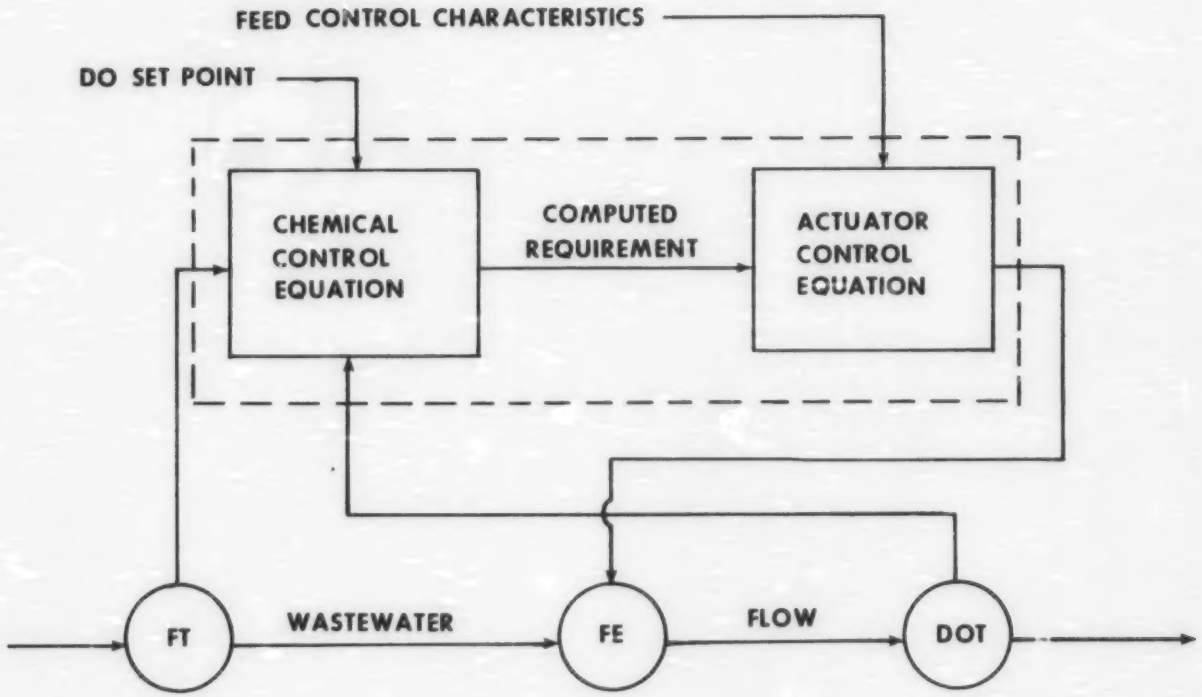

Figure 7. Dissolved oxygen control loop.

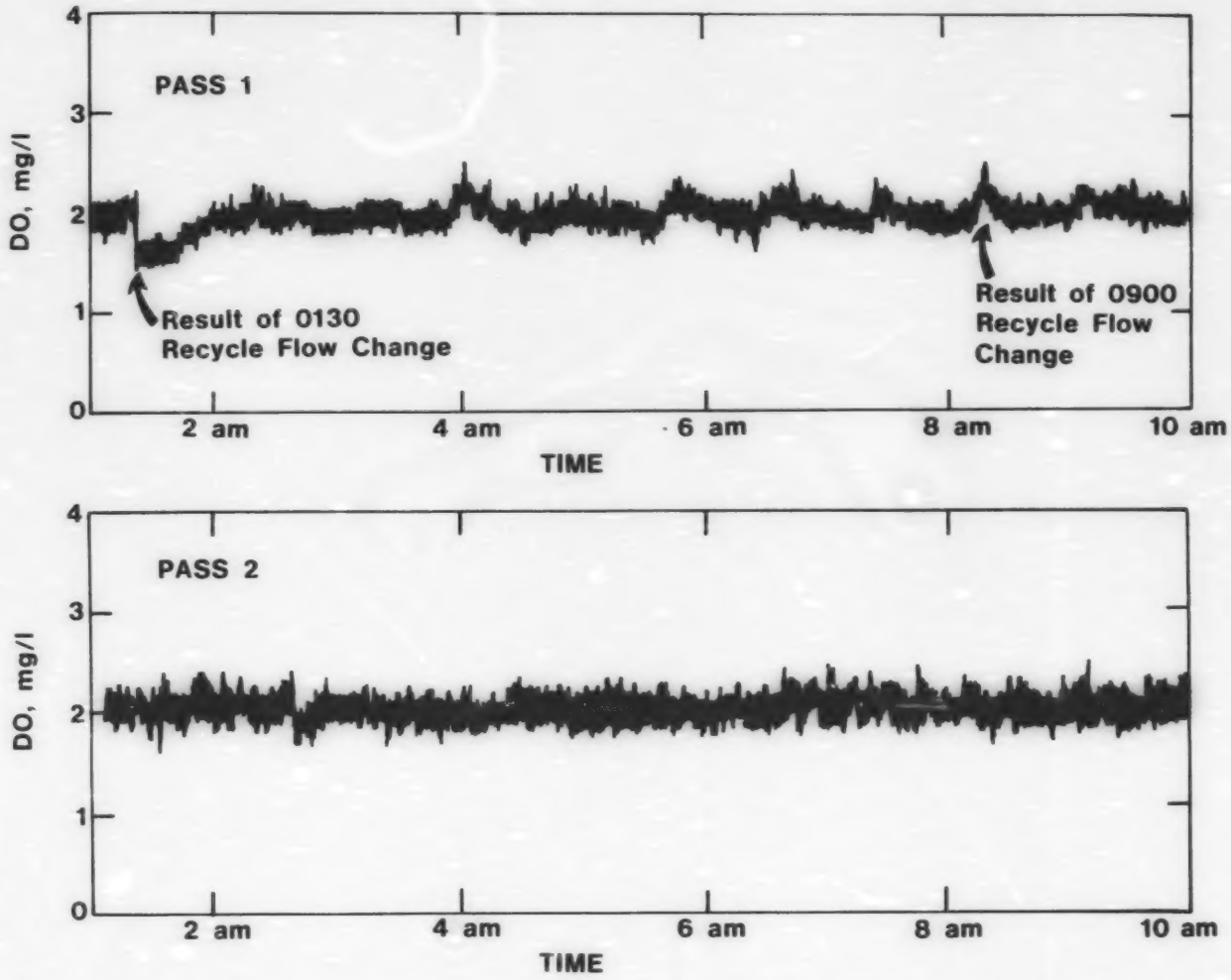

Figure 8. Dissolved oxygen under automatic control.

a degradation of control from simple feedback control. The highest degree of control was achieved with F(Q) proportional to the quadratic root of the process flow with a low limit setting corresponding to the air requirement of the system at zero process flow (Figure 9). The resultant relationship was a moderate rise in air flow with increasing process flow in the low process flow range. This rise slowed and essentially flattened out as the process flow approached maximum.

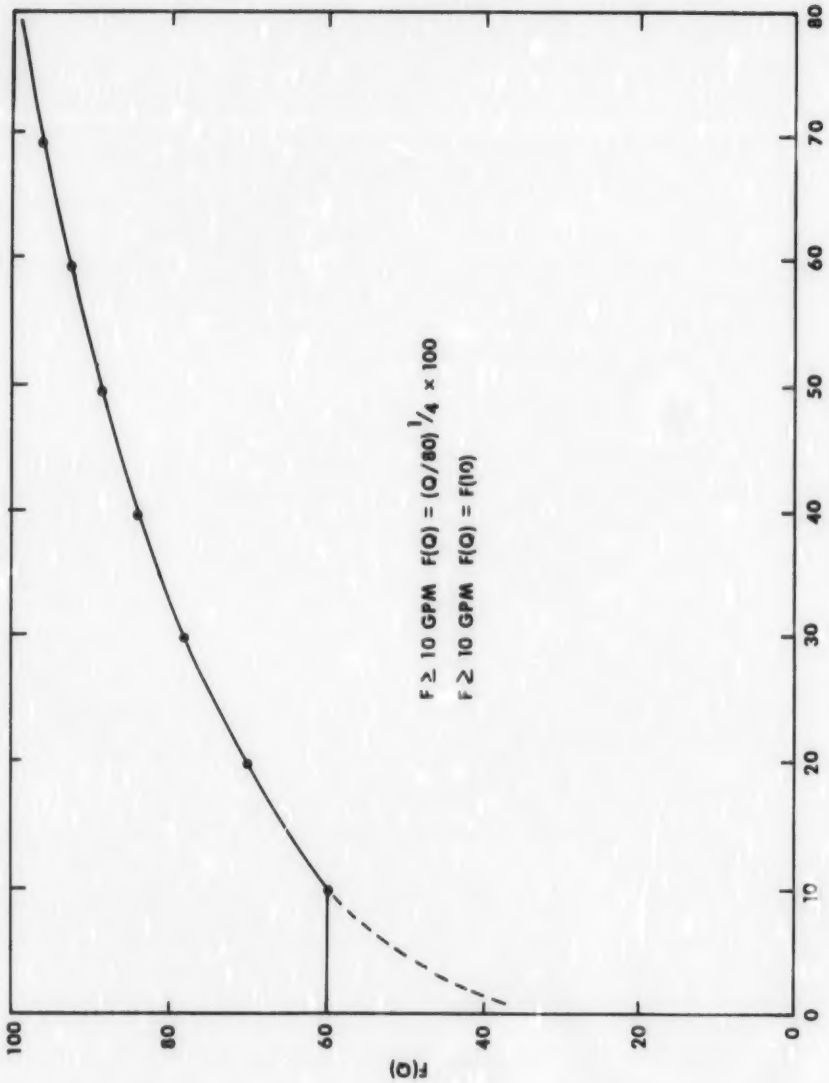

Figure 9. Flow compensation for dissolved oxygen control.

SECTION 6

RESULTS

PHYSICAL-CHEMICAL SYSTEM

After the completion and testing of the computer control program the physical-chemical system was operated continuously with three different control approaches: 12 days of manual control, 9 days of digital control, 6 days of analog control. Unfortunately, the development of the digital control program required more time than originally planned. The remaining available resources and the required task of automation of the pilot plant's three-stage activated sludge system limited the operating time for evaluation of the digital control system on physical-chemical treatment.

In the early work on analog control in physical-chemical treatment, the basic physical-chemical system, except for breakpoint chlorination, could be operated manually or by feedback analog control. The control of breakpoint chlorination by feedback analog control, however, was not possible during changes in process flow. The feedforward-feedback approach developed for successful computer control of breakpoint chlorination was also applied to the manual and analog methods. In manual operation, the operator could provide a feedforward control action as long as the flow pattern was known and involved discrete flow changes. Thus, the system performance under manual, analog, and digital control, was sequentially tested on the complete physical-chemical system for simple step diurnal flow variations.

These first continuous control studies on the entire physical-chemical system were performed with a simple diurnal flow variation in which step flow changes were applied manually on a specified schedule across the system (Table 3). The pilot plant operators had prior knowledge of the flow and flow changes. The digital process in the final testing program responded satisfactorily to gradual and continuous changes in flow as well as to step changes. The flow changes represented a series of steady operations in which the pilot plant operator during manual operation could readjust the operating conditions at each step change in flow and satisfactorily operate even the chlorination process.

The average residuals and removal efficiencies for operation at pH 11.6 in lime clarification, pH 9.8 in recarbonation (9.4 in manual operation) and pH 7.0-7.4 in breakpoint revealed that all control approaches for the step variation in flow produced very satisfactory continuous operation with accumulative final removals of approximately 90 percent of the total nitrogen

TABLE 3. OPERATING CONDITIONS FOR THE PHYSICAL-CHEMICAL SYSTEM

	Flow l/min (gal/min)	Loading
Clarification (two-stages)	85.1 min (22.5)	26.5 $m^3/day/m^2$ (625 gpd/ft^2)
	125.5 avg (33.2)	40.6 $m^3/day/m^2$ (996 gpd/ft^2)
	198.3 max (52.5)	64.2 $m^3/day/m^2$ (1575 gpd/ft^2)
Filtration	85.1 min (22.5)	81.5 $l/min/m^2$ (2.0 gpm/ft^2)
	125.5 avg (33.2)	118.0 $l/min/m^2$ (2.9 gpm/ft^2)
	198.3 max (52.5)	187.0 $l/min/m^2$ (4.6 gpm/ft^2)
Absorption	85.1 min (22.5)	187.0 $l/min/m^2$ (4.6 gpm/ft^2)
	125.5 avg (33.2)	277.0 $l/min/m^2$ (6.8 gpm/ft^2)
	198.3 max (52.5)	436.0 $l/min/m^2$ (10.7 gpm/ft^2)

98 percent of the total phosphorus, and more than 95 percent of the organics from the wastewater (Table 4). The final residual concentrations and the accumulative percentage removals for the short study did not reveal any significant differences in the system performance under the various control approaches. Further study with unknown step and gradual continuous changes in flow are necessary to fully assess and compare the capabilities of the three control approaches for continuously producing high-quality water.

The average lime dosage required to achieve a wastewater pH of 11.6 was 263 mg/l for an average influent alkalinity of 113 mg/l during digital control and 331 mg/l for an average influent alkalinity of 131 mg/l during analog control. Conversion of the analog lime dosage to equivalent dosage for the influent alkalinity during digital control produced a comparable lime dosage of 283 mg/l during the analog operation. Nearly two years of operation of the physical-chemical system with manual or manual-analog operation of the lime feeding system revealed a wide range and variability in the lime dosage and the resulting wastewater pH (240 mg/l to 385 mg/l at pH 11.3 and 289 to 360 mg/l at pH 11.7). Similar wide variability occurred in the CO_2 dosage. The variability in the chemical dosage was related to mechanical difficulties in control and measurement of the chemical feeds as well as to variations in the alkalinity of the wastewater itself.

The tests using the computer for data acquisition indicated that the digital control produced the smallest pH variation (usually ± 0.037 pH units under flow or set point change) and a lime dosage at the low end of the observed lime dosage range. The pH deviations for manual and analog control were ± 0.2 pH units and ± 0.1 pH units respectively. Long-term operation, however, with careful data acquisition is required to evaluate the statistical effectiveness of the control approaches for minimizing the chemical dosages.

Previous laboratory work (5) revealed that the Cl_2 dosage for breakpoint chlorination varied with the degree of pretreatment before chlorination with

TABLE 4. REMOVAL EFFICIENCIES FOR THE PHYSICAL-CHEMICAL SYSTEM

	TOC		BOD		COD		SS		P		Total N	
	mg/l	%	mg/l	%	mg/l	%	mg/l	%	mg/l	%	mg/l	%
Manual												
Raw	82	--	123	--	260	--	145	--	6.8	--	21.4	--
Screened	79	4	118	12	254	2	142	2	6.4	5	21.5	--
Clarified	32	61	35	72	93	64	115	26	1.05	85	18.4	14
Filtered	13	84	12	90	43	89	4	97	0.20	97	14.4	33
Chlorinated	14	83	--	--	36	86	7	95	0.16	98	2.9	86
Adsorbed	3	96	3	98	13	95	3	98	0.13	98	2.2	90
Digital												
Raw	58	--	83	--	182	--	114	--	5.2	--	17.0	--
Screened	56	--	85	--	191	--	127	--	5.2	--	16.7	--
Clarified	17	71	23	72	48	74	69	39	0.36	93	11.6	32
Filtered	9	84	10	88	28	85	8	93	0.13	98	11.3	34
Chlorinated	11	81	--	--	25	86	3	97	0.16	97	2.7	84
Adsorbed	2	97	4	95	10	95	9	92	0.10	98	1.6	91
Analog												
Raw	75	--	114	--	245	--	121	--	6.7	--	21.5	--
Screened	72	4	102	8.6	239	2.5	107	11.5	6.4	4	22.0	--
Clarified	18	76	22	81	47	81	16	87	0.29	96	15.9	26
Filtered	15	80	17	85	39	84	4	97	0.20	97	14.9	31
Chlorinated	14	81	--	--	33	87	3	98	0.23	96	3.4	84
Adsorbed	4	95	4	96	10	96	3	98	0.16	98	2.3	89

a $Cl:NH_3$-N weight ratio of approximately 8:1 for breakpoint of lime clarified and filtered secondary effluent and 9:1 for lime clarified and filtered raw wastewater. The earlier work also revealed that rapid mixing and pH control was also required to minimize undesirable side reactions.

In the study of the different control approaches, the free residual chlorine after breakpoint was controlled to less than 10 mg/l and usually to less than 6 mg/l. The total Cl_2 dosage for breakpoint of 15 mg/l of NH_3-N was about 140 mg/l. While digital operation gave the best control of free residual chlorine, usually to within ± 2 mg/l of the set point under steady state flow, step changes in flow produced loss of control with long recovery times.

The use of the computer's continuous data acquisition capabilities, however, revealed an effect on chlorine dosage not known previously (Figure 10). Flow increases through the static mixer used as the breakpoint reactor produced a decreasing ratio of $Cl:NH_3$-N.

The high-shear energy at the higher flow rates (high Reynolds numbers) and the short reaction time in the static mixer produce more rapid mixing and pH control and thus reduced the reaction period for undesirable side reactions. These side reactions all consume Cl_2 and increase the ratio of

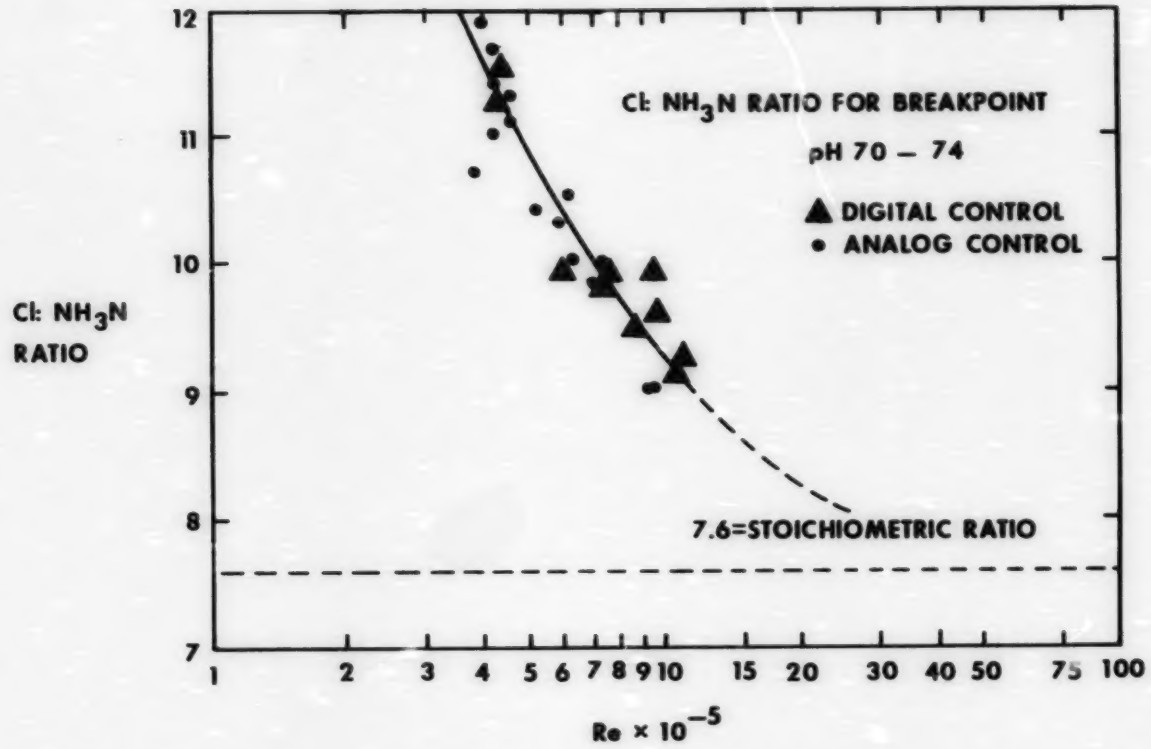

Figure 10. Chlorine dosage ratio in flow rate.

$Cl:NH_3$-N required to achieve breakpoint. The change in $Cl:NH_3$-N dosage with flow through the reactor can be most readily introduced into the digital control model to improve the control performance.

THREE-STAGE ACTIVATED SLUDGE SYSTEM

Following the digital application to the physical-chemical system, computer control of the three-stage activated sludge treatment system was initiated. This multi-stage activated sludge system with final filtration met the proposed District of Columbia discharge standards and was the one selected for the $812 m^3$/min (309 mgd) Blue Plains Sewage Treatment Plant. The three-stage system was normally operated under manual-analog control with process flows similar to those of the physical-chemical system and the diurnal flow pattern imposed is shown in Figure 11. Again, as in earlier work, the pilot plant operators had prior knowledge of the flow and flow changes.

The average residuals and removal efficiencies revealed that manual-analog and digital control approaches for the step variation in flow produced very satisfactory continuous operation with accumulative final removals of approximately 92 percent of the total nitrogen, 97 percent of the total phosphorus and more than 98 percent of the BOD from the wastewater (Table 5). As in the case of the physical-chemical system, this study did not reveal any significant differences in the system performance under either control approach. The manual-analog control normally employed in the system included analog control of chemical feeds and manual control of D.O. Total manual control was never attempted.

The modified aeration stage, operated at an SRT of approximately one day with mineral addition, exhibited excellent stability under both manual and digital control and produced a satisfactory effluent for subsequent processes in the three stage system. As previously mentioned, dissolved oxygen control in this process was difficult with step changes in solids concentration and/or flow, however digital control maintained D.O. to within ± 0.5 mg/l of the set-point. A higher degree of control could perhaps be achieved if additional sensors had been used in feedforward/feedback control mechanisms such as a TOC analyzer or a suspended solids sensor. However, those additional sensors were not necessary for adequate control. Manual control of D.O. could only be maintained to within ± 1.5 mg/l of the setpoint, and suggested that energy consumption could be reduced through automated D.O. control strategies.

$FeCl_3$ addition to this modified aeration was accomplished effectively under both manual and digital control. With $FeCl_3$ dosage equal to a 1:1 mole ratio Fe/P, modified aeration removed approximately 83 percent of the BOD_5, 72 percent of the phosphorus, and about 31 percent of the total nitrogen.

The subsequent nitrification process with the pH controlled to 7.0-7.2 by an average addition of 60 mg/l of dry CaO produced essentially complete nitrification and essentially complete removal of carbonaceous BOD_5. Flow proportioned lime addition for control of pH produced fluctuations of ± 0.2

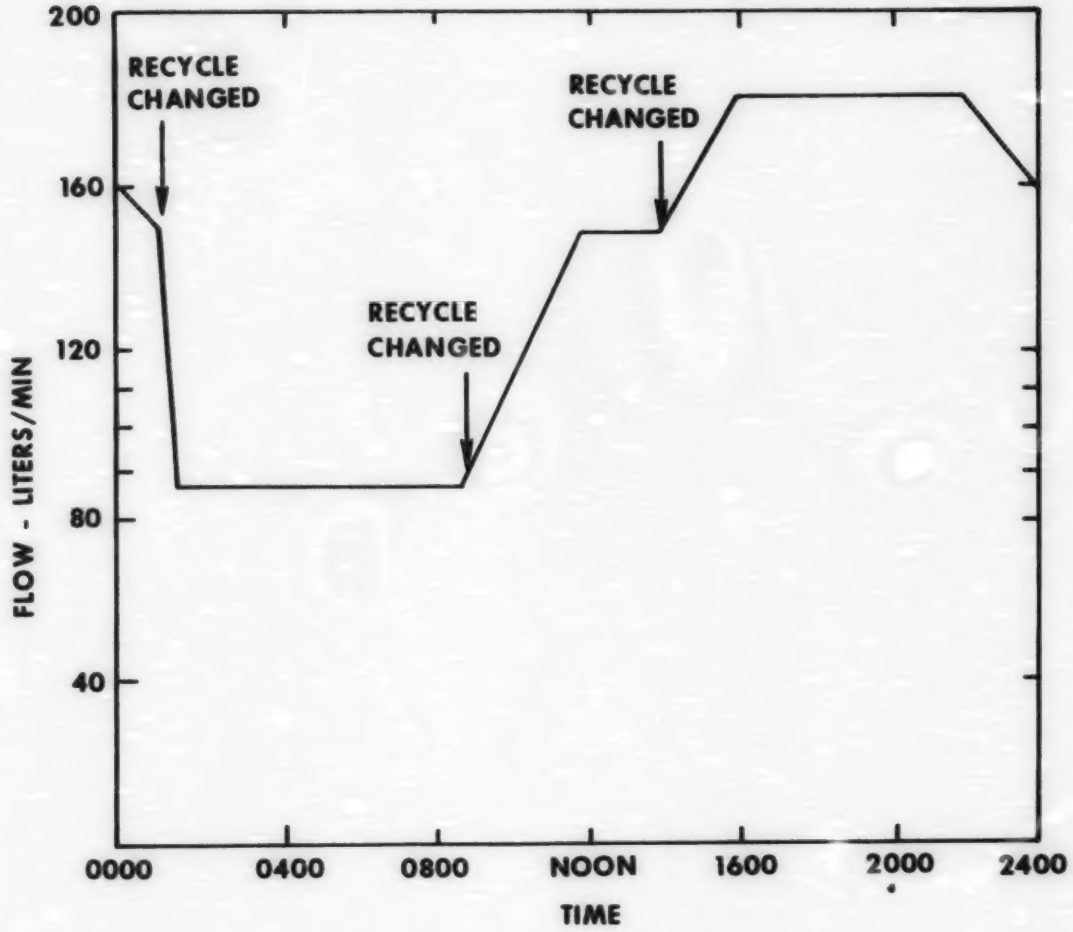

Figure 11. Diurnal flow pattern.

TABLE 5. THREE STAGE ACTIVATED SLUDGE SYSTEM REMOVAL EFFICIENCIES

EFFLUENT	TOC		BOD		COD		SS		P		Total N	
	mg/1	%	mg/1	%	mg/1	%	mg/1	%	mg/1	%	mg/1	%
Manual*												
Primary	76.7	---	111	---	238	---	110	---	6.9	---	23	---
Modified Aeration	18.9	75.4	11.7	89.5	42.3	82.2	13	82	1.9	80.3	14.9	35.3
Nitrification	7.5	90.2	10.9	90.2	17.7	92.6	7.5	93.2	1.2	84.3	14.2	38.6
Denitrification	8.8	88.5	8.5	92.4	19	92	14.1	87.3	0.7	90.9	2.1	91.0
Filtration			2.0	98.1					0.2	98.1	1.5	93.6
Digital**												
Primary	64.5	---	94	---	218	---	104	---	6.2	---	21.6	---
Modified Aeration	19.0	70.5	15.1	83.9	47.3	78.3	18	82.6	1.6	74.2	14.7	31.9
Nitrification	6.9	89.3	10.7	88.6	17.0	92.2	7	93.3	1.1	82.3		
Denitrification	7.9	87.8	8.2	91.3	20.4	90.6	17.7	83.0	0.7	88.7	1.3	94.0
Filtration			1.9	98.0					0.1	98.4	1.7	92.1

* June, 1973
** July-August, 1973

pH units from the setpoint. Operating under digital control, the computer held the pH to within ± 0.03 pH units from the setpoint and control was maintained with only routine cleaning and calibration of the process flow meter and pH sensor.

The denitrification process with methanol addition removed an average of 94 percent of the nitrate nitrogen with an average of approximately 0.7 mg/l of residual NO_3-N. A dosage of four units of methanol (by weight) per unit of NO_3-N produced essentially complete denitrification. Flow-proportional addition of methanol later modified to mass-proportional addition produced high removal efficiencies but no higher than those achieved under flow proportional analog control of the feed rates. Alum addition in the denitrification process at an Al:P mole dosage ratio between 3:1 and 5:1 reduced the effluent phosphorus by about 40 percent. No significant difference in process performance was detected under digital or manual control. The real impact of the alum addition was to insure good phosphorus and solids removal by the final filtration process.

Filtration of the denitrified effluent produced a final effluent that consistently exceeded the discharge standards for the proposed new plant in Washington, D.C. The residual BOD_5 averaged 2 mg/l; the total nitrogen, 1.6 mg/l; and the total phosphorus, 0.2 mg/l as P.

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